Structural Summarization of Semantic Graphs

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Outline

1. **Motivation**: **data discovery** in semantic-rich RDF graphs
2. **Framework**: **quotient summaries**
   - Smaller graph which represents the original one in some sense
3. **Proposal**: use **property cliques** for summarizing **explicit** and **implicit** data
4. Summarization **algorithms**
5. Perspectives

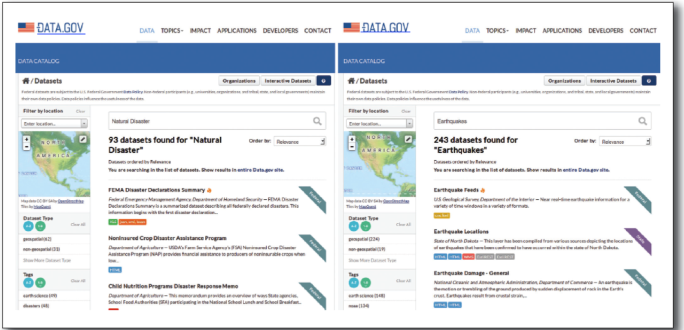
Joint work with François Goasdoué (U. Rennes 1 and Inria), Paweł Guzewicz (U. Paris Saclay and Inria), and Šejla Čebirić (U. Paris Saclay and Inria) [ČGM15a, ČGM15b, ČGM17a, GM18, PGA+18]

Part I

Motivation: data discovery in RDF graphs

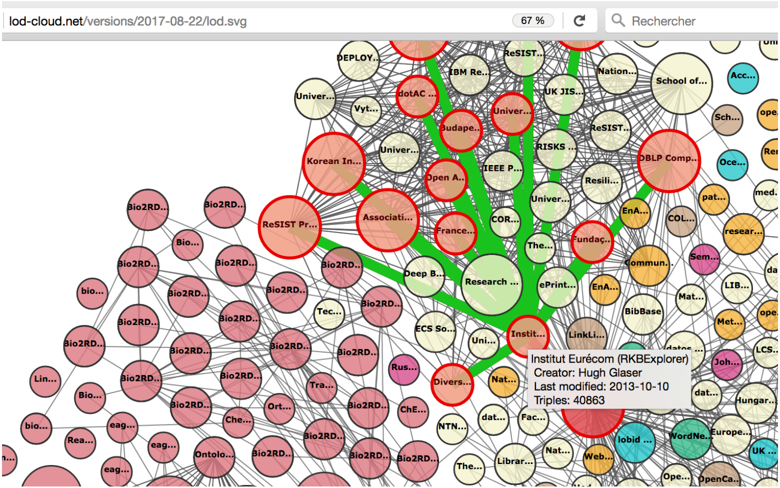
Big Data needs semantics

AI Magazine, Spring 2015



RDF graph discovery

An RDF graph can be large and complex, lack a fixed schema, include many heterogeneous values...



RDF summaries

Simplified views of an RDF graph [ČGK+18]

- Most often, a summary is also a **graph**, and/or: **statistics**, **patterns**...
- Summarize: the **data**, the ontology, both
- Many prior works on graph summarization applied to RDF

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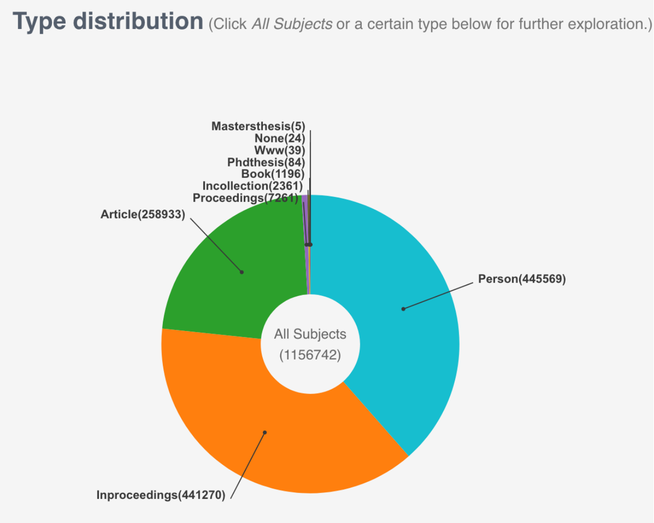
Summary uses:

1. For **query processing**: give direct access to a group of nodes summarized together, detect empty queries...
2. For **data discovery**: help identify interesting structure or patterns in the data

RDF graphs are often structurally heterogeneous

Subject types in DBLP bibliographic data:



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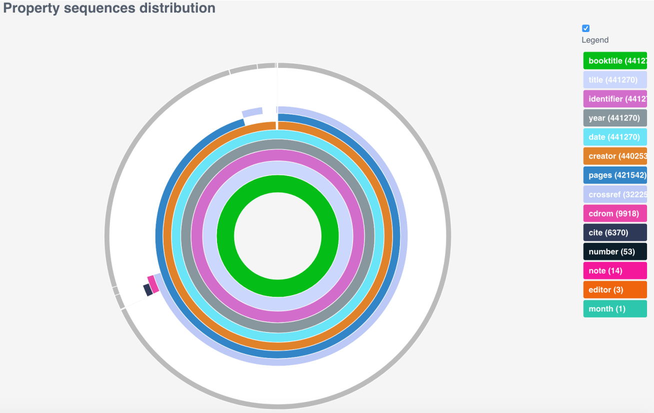
Data properties of DBLP conference articles:



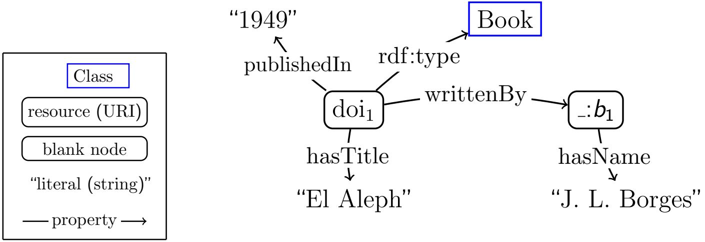
Our goal

Define **structural summaries** which:

- resist to **heterogeneity**
- flexibly take into account **RDF types**
- allow summarizing **implicit triples**
- can be **implemented efficiently**

The Resource Description Framework (RDF)

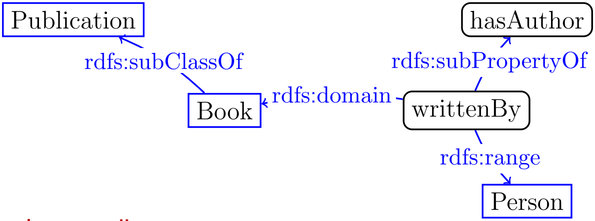
RDF graph: set of triples



RDF Schema

We consider **RDFS** deductive constraints, stating connections between classes and properties

Constraint	Triple	OWA interpretation
Subclass	c_1 rdfs:subClassOf c_2	$\mathsf{c}_1 \subseteq \mathsf{c}_2$
Subproperty	p_1 rdfs:subPropertyOf p_2	$\mathsf{p}_1 \subseteq \mathsf{p}_2$
Domain typing	p rdfs:domain c	$\Pi_{\text{domain}}(\mathsf{p}) \subseteq \mathsf{c}$
Range typing	p rdfs:range c	$\Pi_{\text{range}}(\mathsf{p}) \subseteq \mathsf{c}$



"Any c_1 is also a c_2"

RDF Schema

Simple language of deductive constraints between classes and properties

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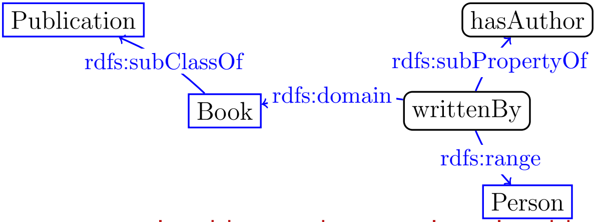

"If two resources are related by $\mathtt{p}_1$, they are also related by $\mathtt{p}_2$"

RDF Schema

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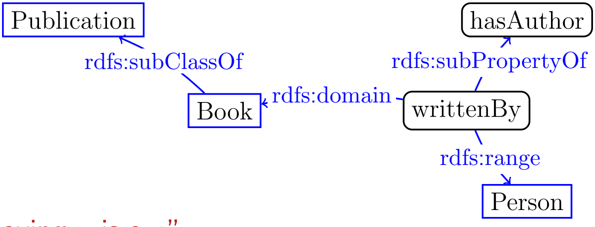

"Anyone having p is a c"

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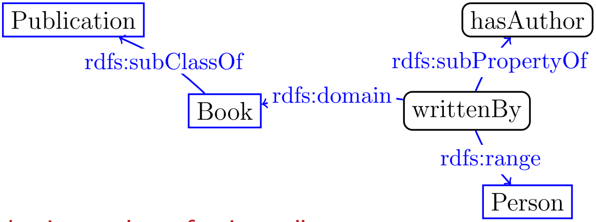

"Anyone who is a value of p is a c"

Open-world assumption and RDF entailment

RDF data model based on the open-world assumption.

Deductive constraints lead to **implicit triples**:
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Open-world assumption and RDF entailment

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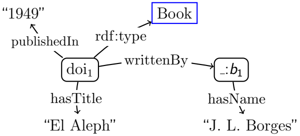
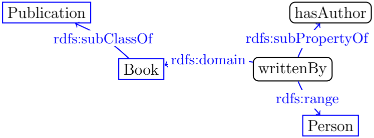
$$\boxed{\begin{array}{c} \textbf{explicit triples} \\ + \\ \textbf{entailment rules} \end{array} \quad \rightarrow \quad \textbf{implicit triples}}$$

Exhaustive application of entailment leads to **saturation** (**closure**)

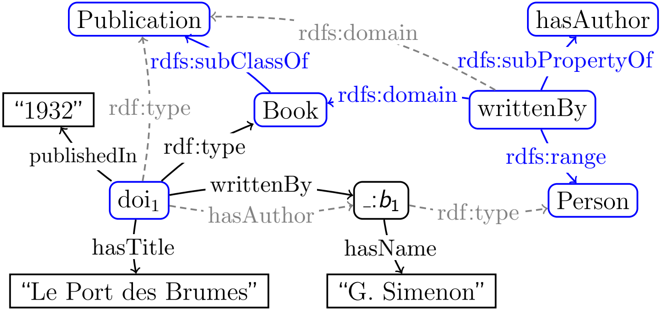
The semantics of an RDF graph $\mathtt{G}$ is its saturation $\mathtt{G}^\infty$

RDF data graph and RDF schema graph:





Saturation of the graph union:



Part III

RDF summarization

RDF summaries

Problem

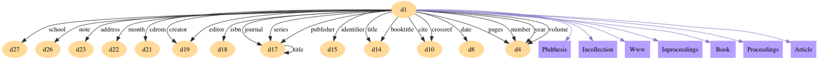
RDF graph `G` is large, heterogeneous, partially implicit.
How to compactly represent all its structure?

Existing solutions

Partial representation (frequent patterns, statistics etc.) e.g., [NM11, LYL13]
Potentially not compact e.g., [GW97, CFKP15]
Only for **explicit data**, e.g., [CDT13, ZDYZ14]

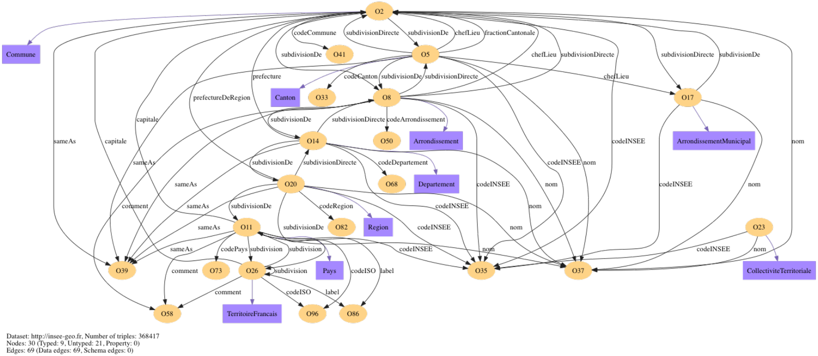
A summary of DBLP data

150M triples



A summary of geographic data

French territory division in regions, departments, urban areas, cities, districts etc.
368K triples



Summarization principle: quotient graphs

Let $\equiv$ be an equivalence relation on the nodes of $\mathtt{G}$.
The **quotient $G_{\equiv}$ of a directed graph G by $\equiv$** is a graph defined as follows:

- $G_{/\equiv}$ nodes: one for $\equiv$ equivalence class of V
- $G_{/\equiv}$ edges: $n^1_{\equiv} \xrightarrow{a} n^2_{\equiv}$ iff $\exists n_1 \xrightarrow{a} n_2 \in \mathtt{G}$ such that n_1 represented by $n^1_{/\equiv}$, n_2 represented by $n^2_{/\equiv}$

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Quotients have interesting summary qualities:

1. **Property completeness:** All G properties appear in $G_{\equiv}$
2. **Size guarantees:** By definition, $G_{/\equiv}$ is at most as large as $\mathtt{G}$ (usually much smaller)
3. **Structure representativeness:** Given a query q, if its structure-only version is empty on $G_{/\equiv}$, then q is empty on G

Common graph quotients: bisimilarity [HHK95]

Two nodes are forward (resp. backward) bisimilar if they have exactly the same incoming (resp. outgoing) paths; $\sim_{\mathtt{fw}}$, $\sim_{\mathtt{bw}}$, $\sim_{\mathtt{fb}}$

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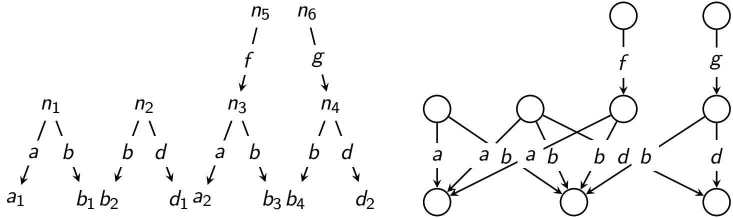

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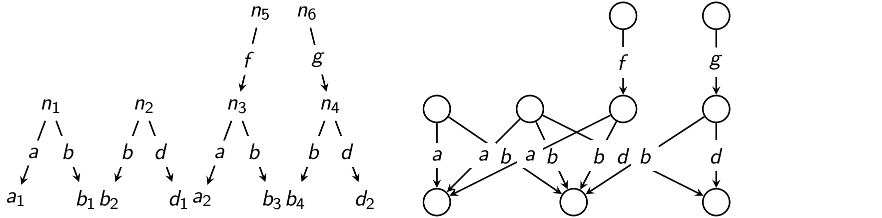

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Requirement 1: We need equivalence relationships robust to structural heterogeneity.

What about type and schema triples?

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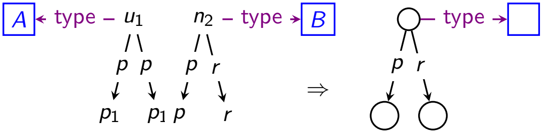
Sample graph G and a possible quotient:



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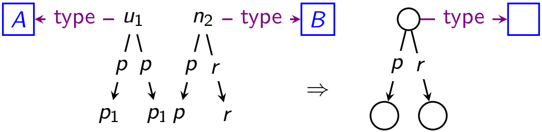

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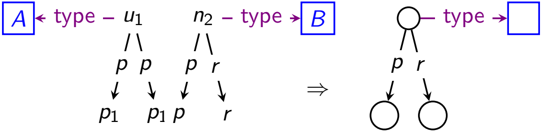

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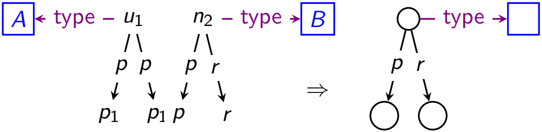

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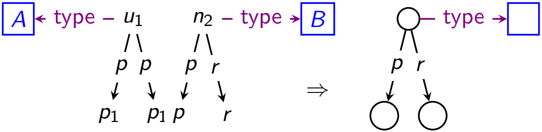


Possible loss of implicit triples

Requirement 2: Avoid schema loss through quotientization

RDF equivalence relation and RDF summaries

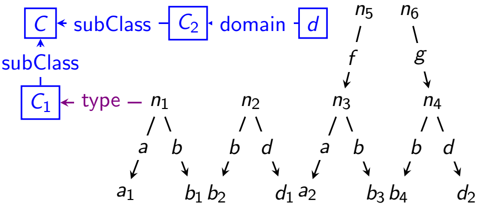
To meet Requirement 2, we define:

1. **RDF equivalence relation**: an equivalence relation on RDF graph nodes such that any class or property node is only equivalent to itself
2. **RDF summary**: a quotient of a graph G by an RDF equivalence relation such that any class or property node is represented by itself.

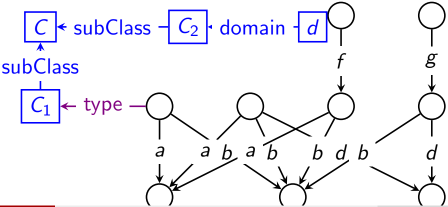
Consequence: For any RDF equivalence relation $\equiv$ and RDF graph G, the schema of $G_{/\equiv}$ is the schema of G.
$\Rightarrow$ No schema compression! (to be rediscussed briefly)

Summarization through an RDF equivalence relation

E.g., let $\equiv_{\texttt{1fb}}$ to be the RDF node equivalence obtained from $\sim_{\texttt{1fb}}$.
Sample graph $\texttt{G}$:



Its quotient through the RDF node equivalence $\equiv_{\texttt{1fb}}$:



Recap

We have seen:

- **RDF node equivalence** and **RDF quotients** $\Rightarrow$ structural representativeness, empty query pruning

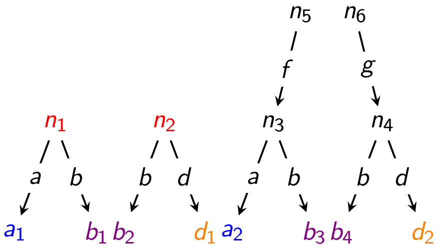
We still need to solve:

- **Requirement 1**: compact (yet preserve structure) even on heterogeneous graphs
- **Requirement 3**: can we summarize implicit triples?

We will address them in this order.

RDF node equivalence based on property cliques

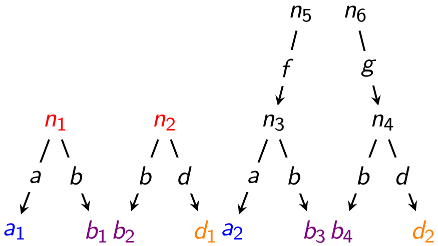
Intuition: n_1, n_2 are "of the same kind"; similarly b_1, b_2, b_3



n_3, n_4 may or may not be of the same kind as n_1, n_2.

RDF node equivalence based on property cliques

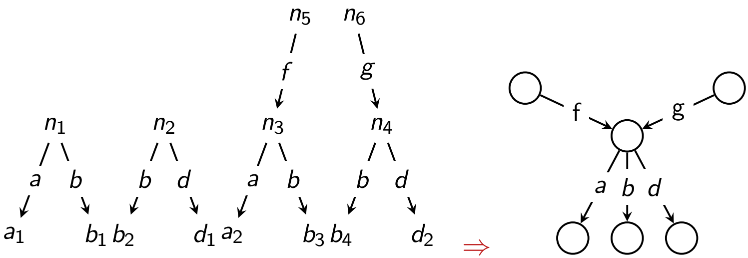
Output property cliques: $\{a, b, d\}$; $\{f\}$; $\{g\}$; $\emptyset$
Input property cliques: $\{a\}$; $\{b\}$; $\{d\}$; $\{f\}$; $\{g\}$; $\emptyset$



Weak clique-based summaries

Two nodes are weakly equivalent ($\equiv_{/\mathtt{W}}$) iff they have **the same input clique or the same output clique or are weakly equivalent to a third one.**

Weak summary $\mathtt{G}_{/\mathtt{W}}$ of the sample RDF graph $\mathtt{G}$:



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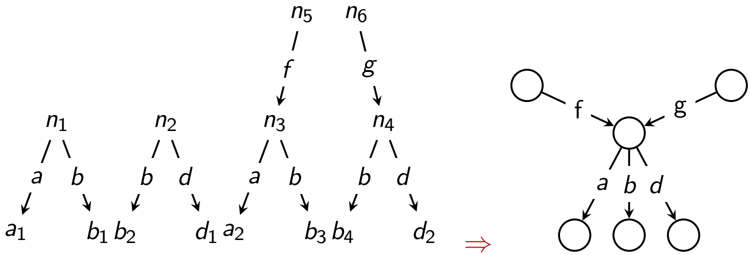
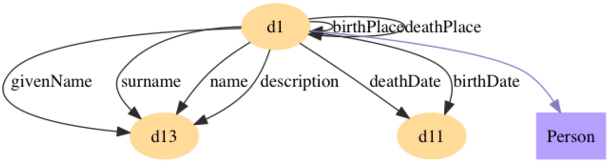


Property: In $\mathtt{G}_{/\mathtt{W}}$, each data property appears exactly once $\Rightarrow$ its nodes are "source of $\mathtt{p}$, target of $\mathtt{p}$" for each $\mathtt{p}$ [ČGM15b].

Weak clique-based summaries

Property: $G_{/W}$ nodes are "source of p, target of p" for each p.

Detecting errors in the data:: why do the birthplace and deathplace loop?



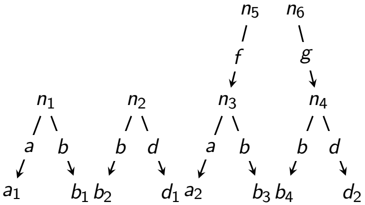
Looking in the data, we find:

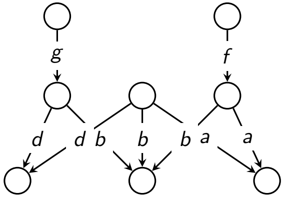
⟨http://dbpedia.org/resource/Kunitomo_Ikkansai⟩ ⟨http://www.w3.org/1999/02/22-rdf-syntax-ns#type⟩ ⟨http://xmlns.com/foaf/0.1/Person⟩ .
⟨http://dbpedia.org/resource/Kunitomo_Ikkansai⟩⟨http://dbpedia.org/ontology/birthPlace⟩ ⟨http://dbpedia.org/resource/Kunitomo_Ikkansai⟩ .

Strong clique-based summaries

Two nodes are strongly equivalent ($\equiv_{\mathrm{S}}$) iff they have **the same input clique** **and** **the same output clique.**

Strong summary $\mathtt{G}_{/\equiv_{\mathrm{S}}}$ of the same $\mathtt{G}$:





Which role should node types play in summarization?

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1. **Data-then-type:** group nodes first by their data triples, then carry the types from each $\equiv$ group to its representative.

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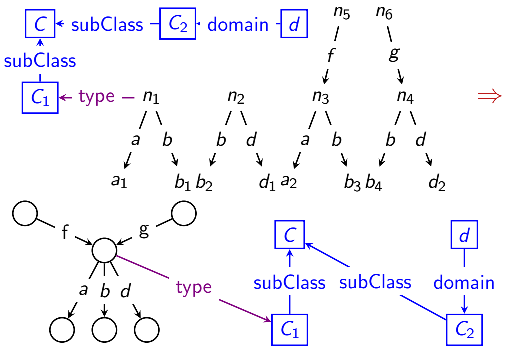
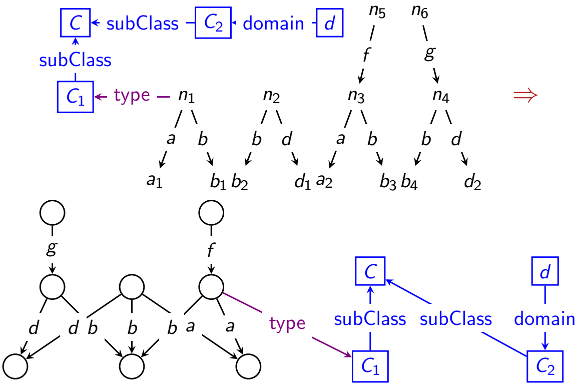
Extended Weak summary:



Adding types after data summarization

1. **Data-then-type:** group nodes first by their data triples, then carry the types from each ≡ group to its representative.

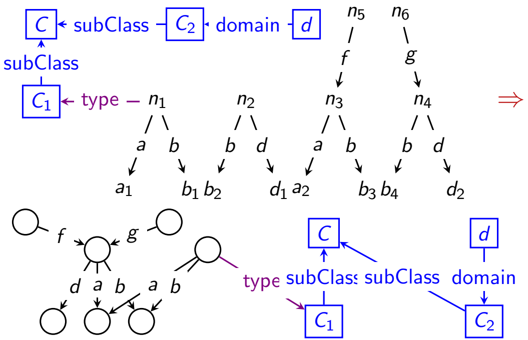
Extended Strong summary:



Giving proeminence to types

2. **Type-then-data:** Group nodes by their type set, and untyped nodes by their data properties.

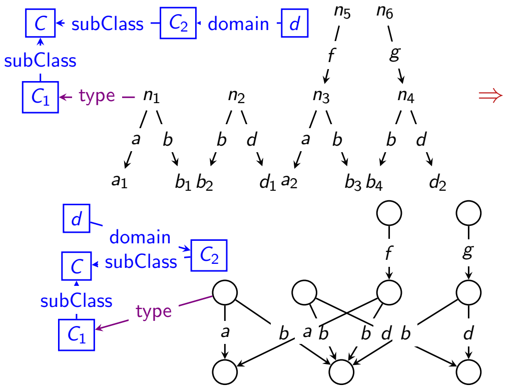
Typed Weak summary $\mathtt{G}_{/\equiv \mathrm{TW}}$ of the sample graph:



Giving proeminence to types

1. **Type-then-data:** Group nodes first by their types. Only untyped nodes are grouped by their data properties.

Typed Strong summary $\mathtt{G}_{/\equiv \mathrm{TS}}$ of the sample graph:



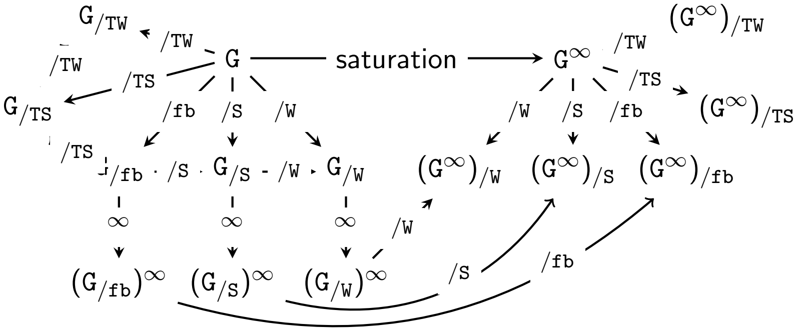
RDF summaries outline

Summary	Weak?	Strong?	Types first?
$\mathtt{G}_{/\equiv \mathrm{W}}$	✓		
$\mathtt{G}_{/\equiv \mathrm{S}}$		✓	
$\mathtt{G}_{/\equiv \mathrm{TW}}$	✓		✓
$\mathtt{G}_{/\equiv \mathrm{TS}}$		✓	✓

RDF summaries outline

Summary	Weak?	Strong?	FW bisim?	BW bisim?	Types first?
$G_{/\equiv \mathrm{W}}$	✓				
$G_{/\equiv \mathrm{S}}$		✓			
$G_{/\equiv \mathrm{TW}}$	✓				✓
$G_{/\equiv \mathrm{TS}}$		✓			✓
$G_{/\equiv \mathrm{fw}}$			✓		
$G_{/\equiv \mathrm{bw}}$				✓	
$G_{/\equiv \mathrm{fb}}$			✓	✓	
$G_{/\equiv \mathrm{fw,T}}$			✓		✓
$G_{/\equiv \mathrm{bw,T}}$				✓	✓
$G_{/\equiv \mathrm{fb,T}}$			✓	✓	✓

Relations between RDF summaries [ČGM17b]



Summary size comparison (more in [ČGM17b])

Graph $\mathtt{G}$	$\lvert\mathtt{G}\rvert$	Summary $\mathtt{G}_{/\equiv}$	$\lvert\mathtt{G}_{/\equiv}\rvert$	$cf_{\equiv}$
DBLP	150,787,464	$\mathtt{G}_{/\mathrm{W}}$	**71**	2,123,767
DBLP	150,787,464	$\mathtt{G}_{/\mathrm{S}}$	**206**	731,978
DBLP	150,787,464	$\mathtt{G}_{/\mathrm{fw}}$	**262,695**	574
LUBM1M	1,227,868	$\mathtt{G}_{/\mathrm{W}}$	**161**	7,579
LUBM1M	1,227,868	$\mathtt{G}_{/\mathrm{S}}$	**207**	5,903
LUBM1M	1,227,868	$\mathtt{G}_{/\mathrm{fw}}$	**1982**	617
LUBM10M	11,990,183	$\mathtt{G}_{/\mathrm{W}}$	**162**	74,013
LUBM10M	11,990,183	$\mathtt{G}_{/\mathrm{S}}$	**206**	58,204
LUBM10M	11,990,183	$\mathtt{G}_{/\mathrm{fw}}$	**24,958**	480
LUBM10M	11,990,183	$\mathtt{G}_{/\mathrm{bw}}$	**6,162**	1,944
LUBM10M	11,990,183	$\mathtt{G}_{/\mathrm{fb}}$	**11,990,076**	1

Summarizing $\mathtt{G}^\infty$

Recall: With an RDF Schema, the semantics of $\mathtt{G}$ is $\mathtt{G}^\infty \Rightarrow$
We really need $(\mathtt{G}^\infty)_{/\equiv}$!

1. Saturate $\mathtt{G}$, then summarize
2. Can we avoid saturating $\mathtt{G}$?...

Summarizing $\mathtt{G}^\infty$

Recall: With an RDF Schema, the semantics of $\mathtt{G}$ is $\mathtt{G}^\infty$ $\Rightarrow$
We really need $(\mathtt{G}^\infty)_{/\equiv}$!

1. Saturate $\mathtt{G}$, then summarize
2. Can we avoid saturating $\mathtt{G}$?...

Shortcut theorem [ČGM17a]

For the summaries $\mathtt{G}_{/\equiv\,\mathrm{W}}$, $\mathtt{G}_{/\equiv\,\mathrm{S}}$, $\mathtt{G}_{/\equiv\,\mathrm{fw}}$, $\mathtt{G}_{/\equiv\,\mathrm{bw}}$, $\mathtt{G}_{/\equiv\,\mathrm{fb}}$:

$(\mathtt{G}^\infty)_{/\equiv}$ is the same as $((\mathtt{G}_{/\equiv})^\infty)_{/\equiv}$

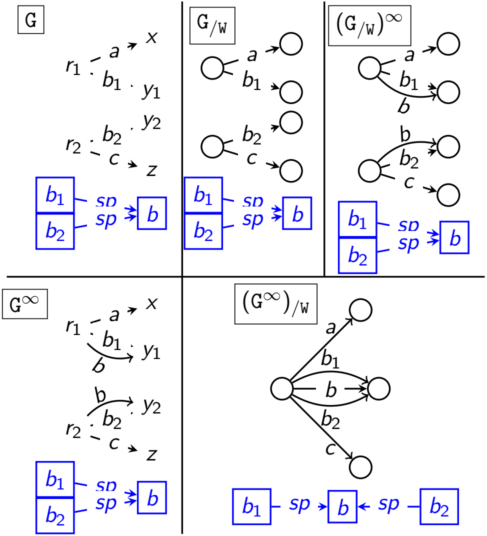
Also: **sufficient condition** for any $\equiv$ to admit the shortcut.

Shortcut path to $\mathtt{G}^{\infty}$

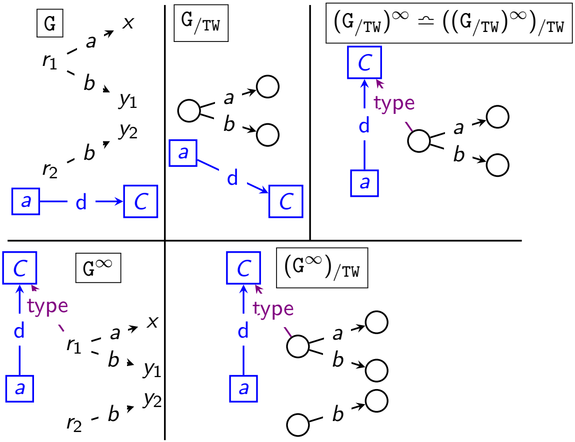
Direct	$\mathtt{G} \rightarrow$ **sat.** $\rightarrow \mathtt{G}^{\infty} \rightarrow$ **summ.** $\rightarrow (\mathtt{G}^{\infty})_{\equiv}$
Shortcut	$\mathtt{G} \rightarrow$ **summ.** $\rightarrow \mathtt{G}_{\equiv} \rightarrow$ sat. $\rightarrow (\mathtt{G}_{\equiv})^{\infty} \rightarrow$ summ. $\rightarrow ((\mathtt{G}_{\equiv})^{\infty})_{\equiv}$

If $\mathtt{G}_{\equiv}$ is much smaller than $\mathtt{G}$, **the shortcut may be faster!**
Up to 20 times in our experiments [ČGM17b]

Shortcut example: $\mathtt{G}_{/\equiv \mathrm{W}}$



Shortcut counter-example: $\mathtt{G}_{/\equiv \mathrm{TW}}$



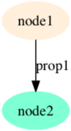
Summarization algorithms

1. **Global algorithms**: visit all $\mathtt{G}$, compute $\equiv$ relation, then traverse $\mathtt{G}$ again and represent each triple in $\mathtt{G}_{/\equiv \mathrm{W}}$
2. **Incremental algorithms**: visit $\mathtt{G}$, compute $\equiv$ and summary based on knowledge gained so far; adjust summary

We devised global and incremental summarization algorithms for $\mathtt{G}_{/\equiv \mathrm{W}}$, $\mathtt{G}_{/\equiv \mathrm{S}}$, $\mathtt{G}_{/\equiv \mathrm{TW}}$, $\mathtt{G}_{/\equiv \mathrm{TS}}$.
Difficulty of incremental summarization: adjusting $\equiv$ and revisiting summarization decisions

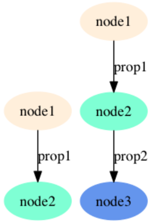
Example: weak incremental summarization (1)

Each color corresponds to a different $\equiv_{\mathtt{W}}$ class



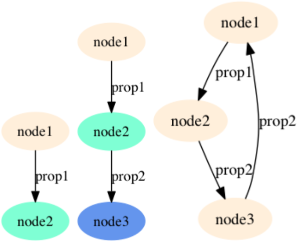
Example: weak incremental summarization (1)

Each color corresponds to a different $\equiv_W$ class



Example: weak incremental summarization (1)

Each color corresponds to a different $\equiv_W$ class



Example: weak incremental summarization (1)

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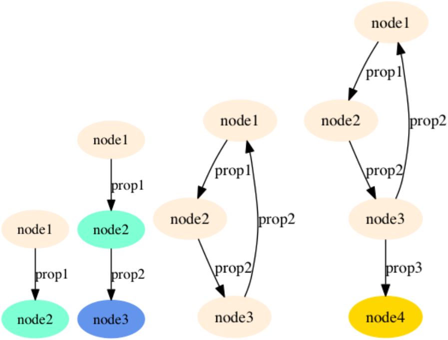

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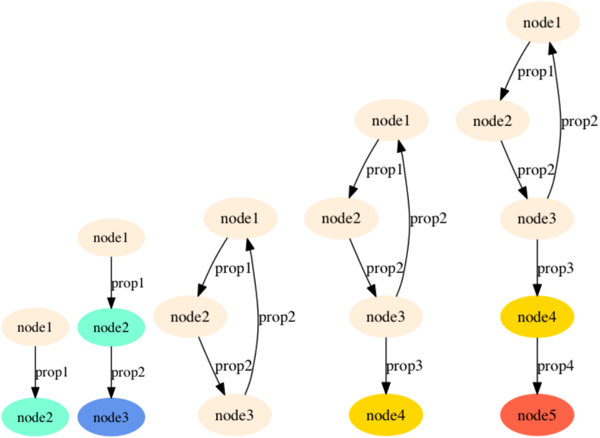
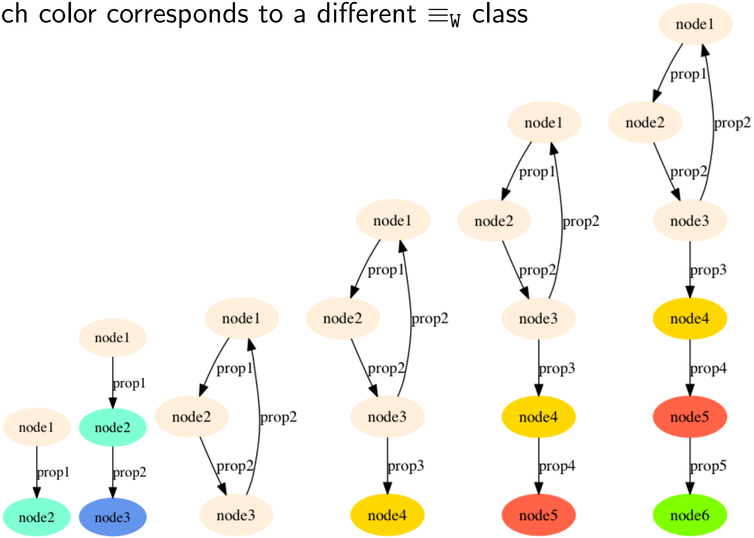


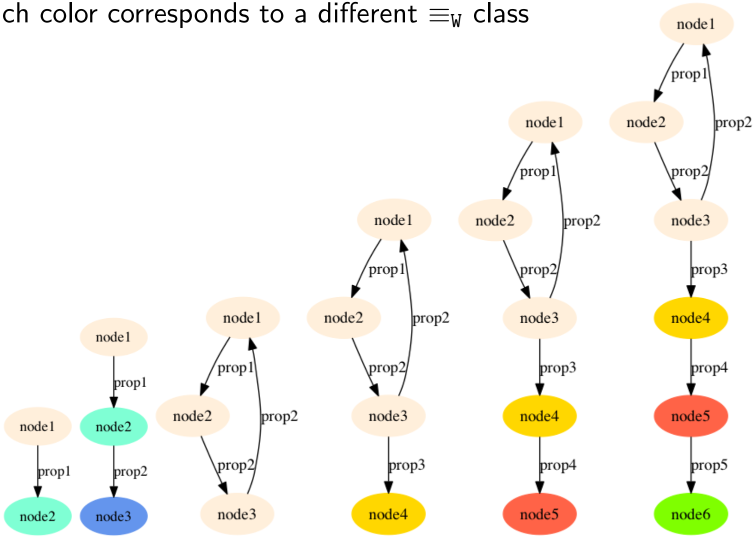
Example: weak incremental summarization (1)

Each color corresponds to a different $\equiv_W$ class

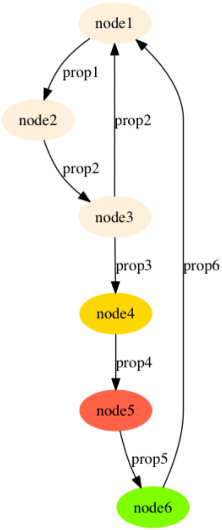


Example: weak incremental summarization (1)

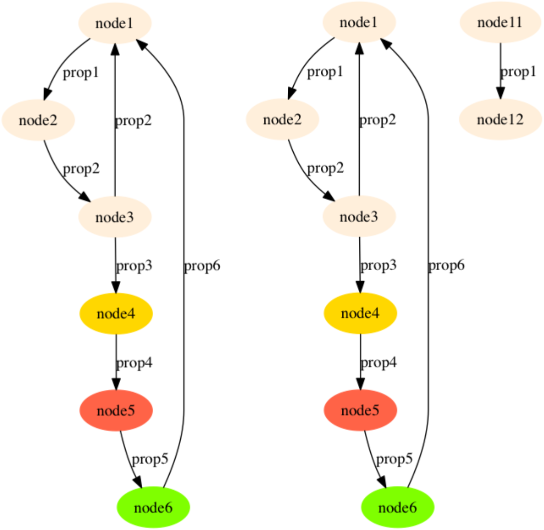
Each color corresponds to a different $\equiv_W$ class



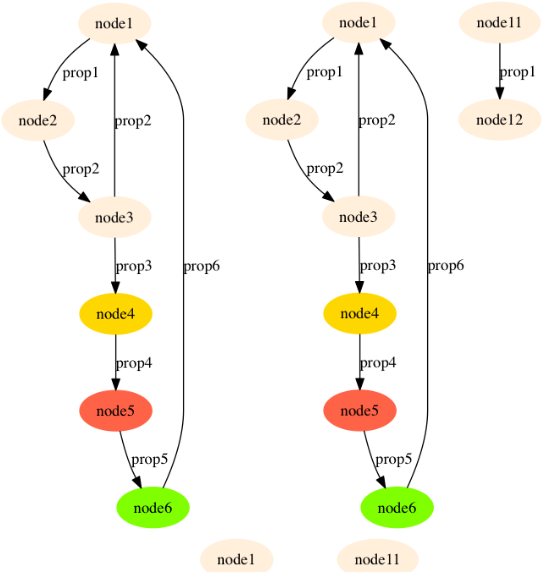
Example: weak incremental summarization (2)



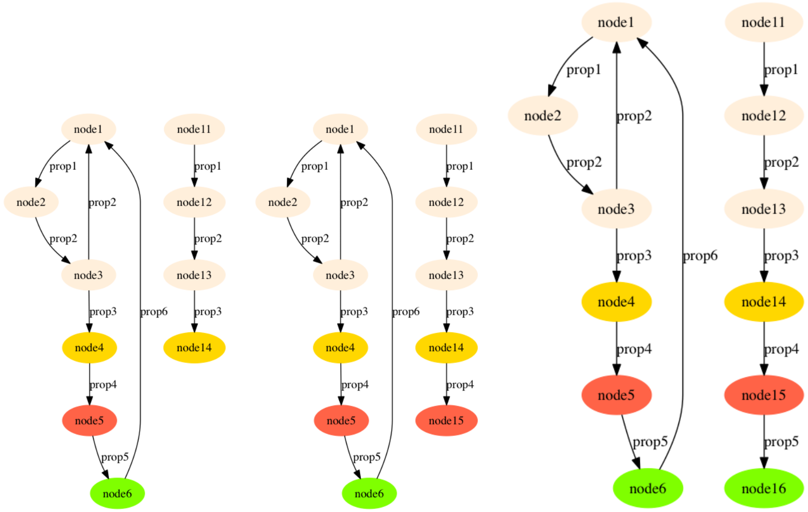
Example: weak incremental summarization (2)



Example: weak incremental summarization (2)

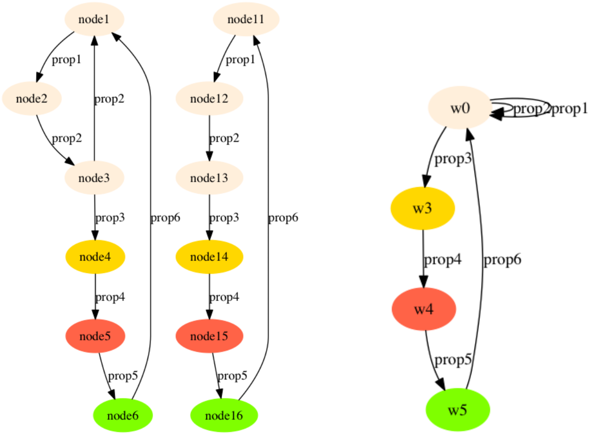


Example: weak incremental summarization (3)



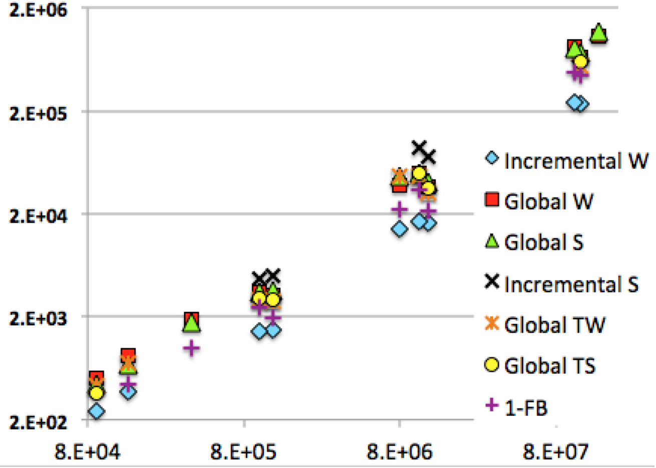
Example: weak incremental summarization (end)

Full graph and its summary:



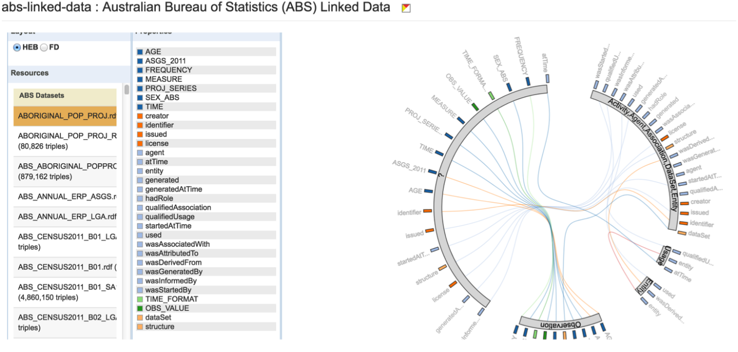
Algorithm scale-up

10^5 to 1.5×10^8 triples



Summary-enabled LOD cloud exploration [PGA+18]

Collaboration with ILDA Inria data vizualization team on LODAtlas
`http://lodatlas.lri.fr/`
Use summary to derive visualisation instead of the original graph (smaller, faster)



Part IV

Conclusion

The need for RDF graph discovery tools

- RDF graphs can be **large and complex**, they lack a prescriptive schema
- Semantic rules lead to **implicit data**
- **Structural quotient summaries** compactly represent graph structure and semantics.
  Available online at: (new version soon)

  https://team.inria.fr/cedar/projects/rdfsummary/
- Type-first summarization variant to cope with large type hierarchies [GM18]
- Integration into LODAtlas platform [PGA$^+$18]

Part V

Perspectives

Ongoing and future work

Ongoing:

1. Experiment with new, parallel summarization algorithms based on Spark
2. Keyword search in RDF graphs based on quotient summaries

Future:

1. Controlled inclusion of data value synopsis in the summary
2. Extension to more expressive ontology languages
3. Integration in a larger platform for summary-based data discovery (with Mirjana Mazuran)
4. Exploration of interesting aggregate view of RDF graphs (with Yanlei Diao)

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